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APPLICATION NUMBER: *60/472,347*
FILING DATE: *May 21, 2003*
RELATED PCT APPLICATION NUMBER: *PCT/US04/15904*

REC'D 02 AUG 2004
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May 21, 2003

TO THE COMMISSIONER OF PATENTS
AND TRADEMARKS
WASHINGTON, D.C. 20231

Docket: W002.PAT-29

Sir:

Transmitted herewith for filing is the
PROVISIONAL PATENT APPLICATION of:
William D. Armstrong et al

For: **DYNAMIC RESONANT SURFACE FLUIDIC SHEAR STRESS SENSOR**

Enclosed are:

- 9 Pages of specification and drawings;
- 1 Cover Sheet;
- 1 Express Mail Certificate;
- 1 Postcard; and
- 1 Credit Card Payment Form in the amount of **$ 80.00** for the Provisional Patent Application Filing fee ($ 80.00).

X APPLICANT CLAIMS SMALL ENTITY STATUS

The Commissioner is hereby authorized to charge any deficiency or credit any overpayment in the filing fees to my deposit account #50-2084. A duplicate of this sheet is enclosed.

Respectfully submitted,

WILLIAM D. ARMSTRONG et al

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant	:	**William D. Armstrong et al**
Filed	:	**Herewith**
For	:	**DYNAMIC RESONANT SURFACE FLUIDIC SHEAR STRESS SENSOR**
Docket No.	:	**W002.PAT-29**

CERTIFICATE OF EXPRESS MAILING

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1. Provisional Patent Application comprising the following pages:
   _9_ Specification and Drawings
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Respectfully submitted,

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DYNAMIC RESONANT SURFACE FLUIDIC SHEAR STRESS SENSOR

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Docket No.: **W002.PAT-29**

Title:
A Dynamic Resonant Surface Fluidic Shear Stress Sensor

Description:

The development of a novel surface shear stress sensor based on a newly formulated dynamic-resonant sensing technique is described here. Using this sensing technique, the development of a lightweight, low-cost wall shear stress sensor capable of fluctuating shear stress measurements is possible. Arrays of such sensors could provide spatial and temporal information about the surface shear stress field. Such sensors are necessary for many flow control applications. For instance, a control scheme for reducing skin-friction drag has been developed that uses wall shear stress as the sensed input to the control system (Lee et al. 1998). Unfortunately, sensors capable of ***quantitative*** fluctuating surface shear stress do not exist. Other potential uses of fluctuating surface shear stress sensors exist in the biomedical and industrial areas where diagnostic sensing, process and system health monitoring, and process control are important.

In the this work, we suggest a novel approach to sensing surface shear stress that employs a resonant dynamic sensor. Dynamic systems operating at or near resonance are very sensitive to small changes in forces. This sensor is specifically designed such that surface shear stress on the surface of the sensor acts to damp the resonant system. By measuring changes in the resonance, the surface shear stress can be determined. Part of the benefit of this dynamic sensor over static force balance sensors is that other forces (such as pressure differences across the sensor due to pressure gradients) do not affect the dynamic motion and thus do not affect the sensitivity to surface shear stress. With this sensor design, ***the ultimate goal is to design a lightweight, inexpensive, scaleable surface shear stress sensor capable of high-bandwidth fluctuating shear stress measurements in many different flows and on many different surfaces.*** To achieve this goal, the sensor must be calibrated both statically and dynamically. Although some methods for in situ dynamic calibration of surface shear stress sensors exist, new approaches may be necessary.

A prototype surface shear stress sensor based on the dynamic-resonant design has been fabricated and tested. Preliminary data obtained with this sensor in a wall jet indicates that the sensor is sensitive to surface shear stress, but the exact physical mechanisms involved are not well understood. More comprehensive testing is required, and development of a detailed model of the device will allow for optimization of the sensor's performance. Further investigation of this sensor may indicate that other similar resonant geometries are better suited for surface shear stress sensing than the current design. It this is the case, other dynamic-resonant geometries will be explored. The benefits of this sensor's dynamic-resonant design are that, unlike many sensors, it is directly sensitive to surface shear stress and thus can provide measurements in flows with varying temperature, varying composition, contamination, etc. Thus, it is expected that this sensor can be applied in an extremely wide range of applications.

The long-range goal of the faculty of the UW ActiveAero Center is the development of system level flow control devices. Such systems are comprised of sensors, actuators, and the control methods. As a result, developing sensing methods appropriate to the flow being controlled is a high priority. Since fluctuating surface shear stress is very sensitive to the state of the boundary layer, its measurement is key to providing the sensing necessary to control wall-bounded flows.

Background and Significance

Significance

Surface shear stress is very sensitive to, and therefore a good indicator of, the flow conditions above the surface. Therefore, miniature surface shear stress sensors could be an effective tool that could be used for diagnostic purposes, flow monitoring, and flow control. However, no well-characterized sensors capable of fluctuating surface shear stress measurements in general flows are available today. Surface shear stress sensors remain an active area of

interest and development, but without novel, thoroughly calibrated, well-characterized sensors, their potential will go unrealized. Although recent work on small-scale sensors has demonstrated some advantages of small size, most of the designs have been miniaturized versions of conventional sensors. The novel sensor described here is specifically designed to take advantage of the small sensor sizes possible with today's manufacturing methods.

If the sensor described here performs as preliminary results would indicate, the impact on many areas could be large. Any process where pressure and mass flow are measured would be a candidate for a surface shear stress sensor. This represents an enormous number of applications. Since it is possible to manufacture these sensors as single sensors, in large arrays, and in sensor/actuator systems, these sensors may be applied to new areas where no equivalent technology exists today. One obvious application for small-scale surface shear stress sensors is the aerospace industry where vehicle health monitoring and flow-control applications (Wright et al., 2002) could benefit from this sensor. A specific application would be sensing system for stall that would be much more sensitive that today's methods. This would be particularly important for high-altitude subsonic aircraft that operate near stall. The medical field also has interest in surface shear stress measurements in arteries where low mean levels of and/or high fluctuations of surface shear stress are associated with plaques that form as part of artherosclerosis (Ku et al., 1985). The industrial field could benefit from such a sensor in process monitoring and control applications. Another application would be sensing surface shear stress in coordination with sensors for detecting chemical and biological agents. The shear sensors would monitor and/or control the air passing by the biological/chemical sensor by sensing the state of the flow.

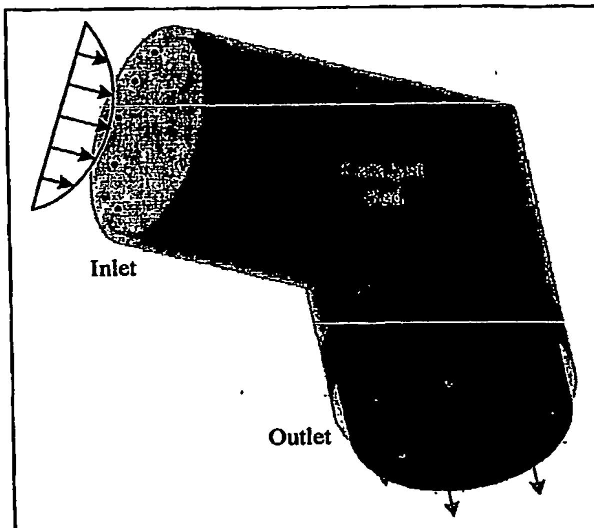


Fig. 1 - Catalyst bed showing sensors at the inlet (blue) and outlet (yellow).

An example where surface shear stress has been applied in an industrial process for monitoring and process control is polymer extrusion (Goldberg et al., 1994). An application with significant potential that could benefit from accurate fluctuating surface shear stress sensing would be catalyst beds (see Fig. 1). In this application, shear flow sensors would monitor the surface shear flow just ahead of or just exiting a flow-through catalyst bed. This will allow for the continuous optimization of the target chemical process in situations where the flow properties are changing due to the degradation of the catalyst media. The sensors may be arranged on the walls or on baffles so that a large matrix of local flow conditions may be continuously measured, which allows for the identification of local flow blockage. The present industrial method of using turbine flow meters or orifice pressure sensors is insensitive to local flow variations, exacts pressure losses, and is prone to breakdown from mechanical failure or chemical attack.

Table 1: Shortcomings of some conventional sensors

Direct-Force Balances	Thermal Sensors	Velocity Profile Measurement
• Small shear force • Pressure gradients • Required gaps • Sensitivity to vibration • Sensitivity to thermal expansion	• Temperature drift • Conduction to substrate • Non-unique calibrations o Reynolds analogy • Sensitivity to unknown fluid composition and dust	• Time-intensive • Mean measurement only • Seeding sometimes required • Fits susceptible to error • Flowfield access required

Background

The measurement of surface shear stress has been studied for over one hundred years. Here, surface shear stress sensors are split into two categories: conventional approaches and small-scale sensors that take advantage of the materials and manufacturing processes now available. Conventional surface shear stress measurement methods pertinent to the current invention are discussed here, and further details are provided by Winter(1977), Haritonidis(1989), and Naughton and Sheplak(2003). The latter reference further discusses recent advances in surface shear stress measurement including advancements in small-scale surface shear stress sensors. Some sensors that have been investigated for years at large scales are being reduced in size to investigate benefits arising from scaling. Direct force balances, thermal sensors, and sensors measuring points in the velocity profile have all been investigated recently at the small-scale level. At the large scale, these sensors suffer from several shortcomings (see Table 1). As a result, measurement techniques such as oil-film interferometry are gaining widespread use for mean surface shear stress measurements (see Naughton and Sheplak(2003) for a description of recent growth in the use of this technique). Due to the nature of the oil-film technique, it is likely that its use will be limited outside the laboratory environment and is not a candidate sensor for small size or fluctuating measurements.

The characteristics of an ideal surface shear stress sensor include:

- High bandwidth (mean and fluctuating measurements)
- High spatial resolution
- Known transfer function
- Traceable calibration (i.e. what was the calibration performed)
- High spatial resolution
- Lightweight
- Low cost
- Easy to integrate
- Robust
- Low power consumption

Although these characteristics are demanding, many of these are realizable in a single sensor with today's materials and technology. The demanding aspect is creating new designs that take advantage of these new technical capabilities.

Benefits of creating sensors at the small scale are possible because of the advances in microelectrical-mechanical system (MEMS) and micromachining technologies now available. The approach to date has primarily been to reduce the size of conventional sensors, and it has met with mixed success. A brief description of three approaches (Velocity-based sensors, force-balance techniques, and thermal sensors) is given below, and the reader is referred to Naughton and Sheplak (2003) for an in-depth discussion.

Over the past two years, miniature velocity measurement sensors (MOEMS - Micro-Optical-Electro-Mechanical Systems) have been introduced (Fourgette et al. 2001, Fourgette et al. 2003). These sensors make streamwise velocity measurements at two or more points in the flow, and, using boundary layer similarity laws, the surface shear stress is inferred. One method uses the diverging fringe method first suggested by Naqwi and Reynolds(1991). Measurements are made in the diverging fringes in the near-wall region (laminar sublayer) of the boundary layer. In this region, velocity increases linearly with distance from the wall, and thus the velocity gradient is constant. Particles passing through these fringes produce a scattered light signal whose frequency is proportional to the velocity gradient. Although particles passing through the different heights have different speeds, they will produce nearly identical signals. Having obtained the velocity gradient, the surface shear stress may be easily calculated. Recent work extends this technique to higher Reynolds number by not limiting the measurement region to the laminar sublayer. Velocities are measured at two points in the boundary layer and Spalding's equation is used to fit the points and to determine the surface shear stress. For both of these methods, MOEMS enables small probe volumes and a compact sensor. The method will measure fluctuations, but their relationship of these fluctuations to variations in surface shear stress needs to be established, particularly for the two-point measurement system. Although these methods show some promise, there are some drawbacks as well. The method requires seeding, and the need for a laser in the system limits how small the sensor can be made. These sensors will be invaluable in the laboratory for evaluating new concepts such as that suggested in the current disclosure, but this sensor is unlikely to attain widespread use outside the laboratory environment.

Small-scale implementations of direct force balance methods have been around for 15 years. Schmidt et al implemented the first prototype sensor in 1988. Subsequent implementations have improved on this original design.

In all these designs, tethers support a floating element. As shear stress is applied to the sensor surface, the sensor deflects laterally. Capacitive (Schmidt et al. 1988), piezo-resistive(Ng et al. 1992), and photo-electric (Padmanabhan et al. 1997) methods have been used to determine the position of the sensor. In another method that has design features that might be included in a MEMS implementation of the current design, Pan et al. (1999) developed a sensor that incorporated an electro-static comb-finger design that could be used for capacitive sensing of floating element position or could be used to actuate the sensor. Of these sensors, only that of Padmanabhan et al. (1997) has been dynamically calibrated (to 4 kHz). A drawback of floating element designs is their limitations in dirty environments due to the necessary gaps between the floating element and the surrounding surface. The sensor of Padmanabhan et al. (1997) required a remote light source that made the sensor sensitive to vibration. In summary, balance techniques appear to show promise, but, in 15 years of development, a prototype with the necessary characteristics for fluctuating surface shear stress measurements has not been developed.

Small-scale silicon thermal sensors offered great promise due to the improved resistance to conduction. As a result, many investigators have attempted to exploit thermal sensors for fluctuating wall shear stress measurement over the past 15 years. In these approaches, a small element is heated to a temperature above that of the flow. Changes in convective heat transfer from the sensor result in changes in the resistance of the heating element. The resistance is thus a measure of the heat transfer and is assumed to be proportional to the surface shear stress through Reynolds analogy. Early sensor designs by Oudheusden and Huijsing(1988) were improved upon by Ho, Tai and co-workers (see, for example Liu 1999). The Ho-Tai group created individual and arrays of sensors, but, in lieu of an in situ dynamic calibration, the sensors' dynamic response was quantified using electronic signal injection, clearly not an appropriate method for these types of sensors. Recent work by Breuer (2000), Cain et al.(2000), and Sheplak et al. (2002) has focused on improved thermal isolation, improved thermal coefficients of resistance, and reduced noise. Sheplak et al. (2002) statically and dynamically calibrated a thermal sensor over a large dynamic range (9 μPa to 1.7 Pa) and obtained a transfer function over a range from 100 Hz to 8 kHz. Rigorous calibrations of sensors such as this are essential in understanding the dynamic response of these surface shear stress sensors. Although much work has been done in thermal sensors, they still have many drawbacks including a lack of understanding of the coupled fluid dynamic/heat transfer process, unsteady conduction to the substrate, temperature drift, and sensitivity to fluid transport properties.

It is clear from the results to date that small-scale surface shear stress sensor development is still a work in progress. Much work has been done on these sensors, but unfortunately, few of the studies have reported rigorous characterization and calibration. One notable exception is the work of Sheplak et al.(2002), but even they concluded that much remains to be understood. Although these methods do show some promise, they are simply extensions of conventional techniques and thus inherit some of the same problems. Although development of these methods should continue, ***it is time to pursue new approaches inherently dependent on small scale.*** The manufacturing capability exists today for constructing arrays of surface shear stress sensors - it is simply waiting for viable sensor designs.

Dynamic-Resonant Surface Shear Stress Sensor Concept

Our preliminary model of surface shear stress sensor utilizes the extremely high sensitivity of a high Q dynamic resonant system to measure the surface shear stress. The system is simple and robust - it contains only 4 major elements. The first element is a very thin, lightweight oscillating plate. Very fine, high tensile strength wires suspend the oscillating plate. The longitudinal motion of the plate is driven near the resonant frequency by a fixed frequency, electromagnetic drive coil. A linear Hall effect transducer continuously measures the position of the device. As the surface plate oscillates parallel to the surface shear vector, time varying shear forces impose drag. The magnitude of the shear drag forces is different at different points within a single cycle. The variation of shear forces within a cycle results in a dampening of the resonant forced vibration of the plate and a consequent change in phase offset. The phase offset is large and easily measured by standard analog or digital electronics.

Fig. 2(a) shows a top view of our preliminary design. The oscillating top plate is located just ahead of an inset plate that contains a small solenoidal winding. During operation, the plate vibrates at approximately 27 Hz with a longitudinal displacement amplitude of approximately three millimeters. Fig. 2(b) shows an oblique view of the solid model for the device. The device requires a vertical inset to accommodate a vertical elastic suspension. The device must be mated to the primary flow surface plate with precision, as the flow must not separate in front of the oscillating plate.

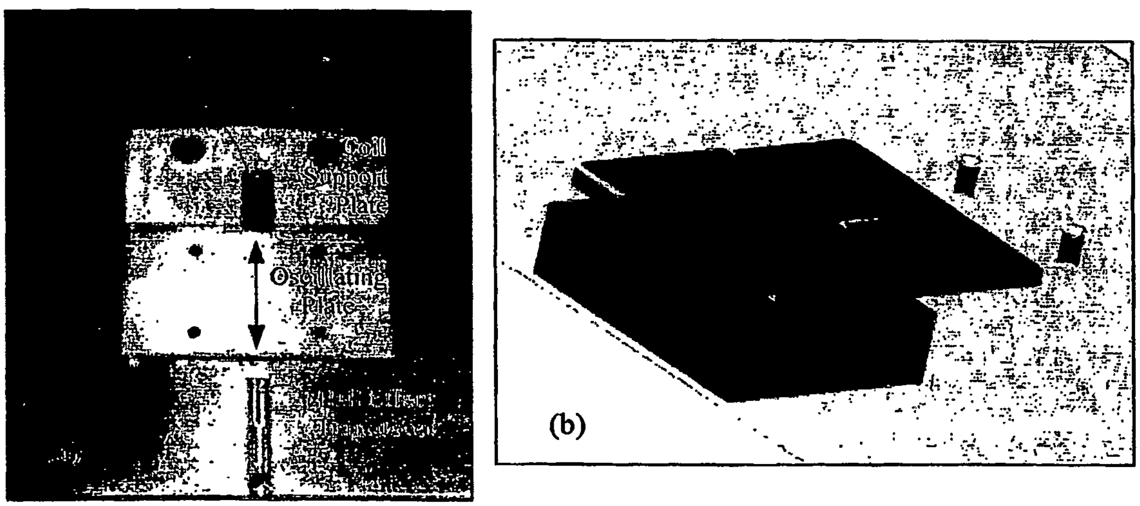


Fig. 2 - Large-scale prototype surface shear stress sensor: (a) image of the sensor, and (b) three-dimensional schematic.

Large Scale Working Model

To investigate the sensitivity of the prototype surface shear stress sensor, it has been tested in a wall jet. Plan and side views of the wall jet are shown in Figs. 3(a) and (b). The size (50 x 100 mm) and location of the sensor relative to the wall jet are schematically shown. Instrument air is supplied to the nozzle from which a thin wall jet issued. As this jet passes over the surface of the plate, a surface shear stress field is created. Note that the streamlines, and thus surface shear stress direction, are not parallel to the jet centerline at all location (although it is close), and that the shear decreases with distance from the exit. Nonetheless, the sensor responds to some average shear across the sensor surface. The surface shear stress magnitude can be changed by varying the supply pressure, which is monitored by a Pitot probe located ~87 mm downstream of the jet exit.

The prototype surface shear stress sensor has been tested over a range of wall-jet pressures. Fig. 4(a) shows the rms voltage output of the Hall effect transducer at various driving frequencies for different jet pressures. It is evident that the magnitude of the resonance decreases with increasing jet pressure (and thus shear) and the peak resonance shifts to lower frequencies. By driving the sensor at the frequency where the rms voltages in Fig. 4(a) all cross (27.305 Hz for this sensor), the rms voltage output stays constant with shear stress. In Fig. 4(b), the effect of increasing shear on the output signal of the Hall effect transducer is shown. The driving voltage is also shown for reference. As the jet pressure increases, the output signal shifts to the right indicating that the phase difference between the driving signal and the plate motion is increasing. In this operational mode, ***the phase offset is a measure of the surface shear stress.***

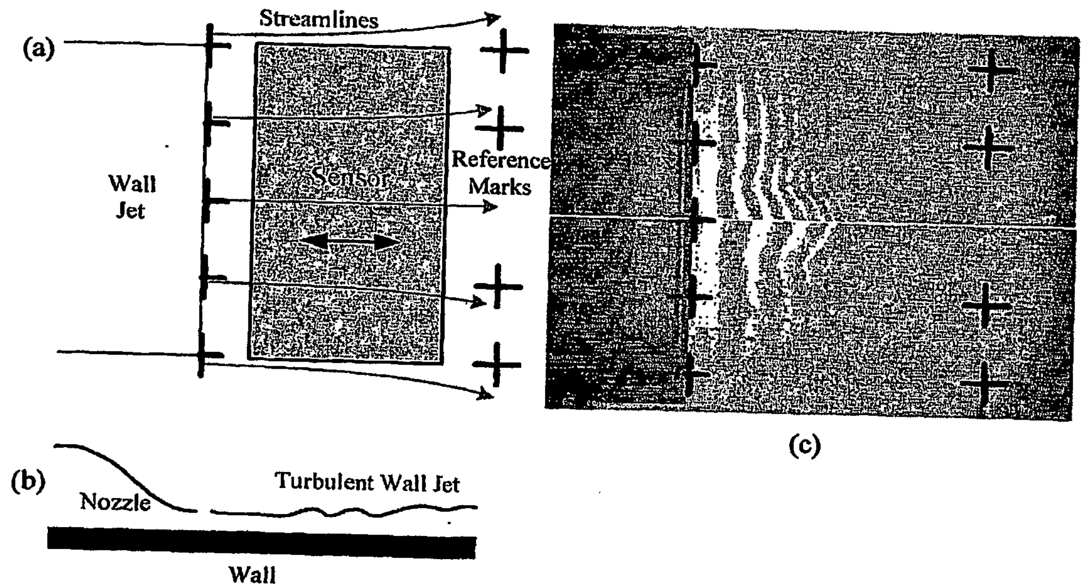
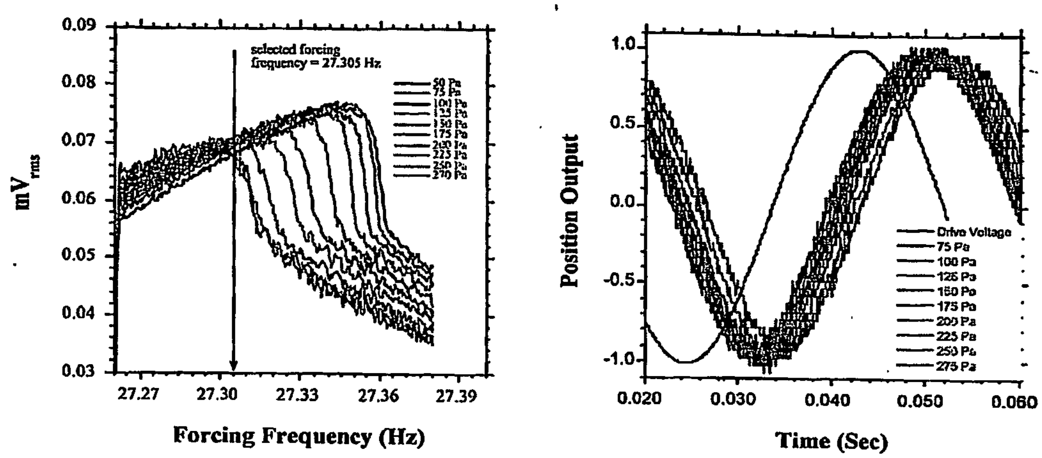


Fig. 3 Wall jet used to investigate surface shear stress sensor response: (a) top view schematic of wall jet showing sensor location relative to jet exit (b) side view of wall jet flow field, and (c) oil-film interferograms taken at 315 s (top) and 585 s (bottom) used to determine the surface shear stress.



(a) (b)

Fig. 4 - Behavior of sensor subject to an excitation: (a) response of sensor to forcing at different levels of surface shear stress, and (b) drive voltage and Hall effect transducer output for different surface shear stress levels. Note that the curves in (b) were obtained at 27.305 Hz driving frequency, shown by the black arrow in Fig. 4(a). The pressures in the legends correspond to Pitot tube measurements in the wall jet.

To quantify the relationship between the phase offset and surface shear stress, oil film interferometry has been used to measure the surface shear stress. Oil-film interferometry is an optical method of measuring surface shear stress, and a description of the technique can be found in Naughton and Sheplak (2003). The method being used to analyze the results shown here is discussed by Alvi et al. (2002). Fig. 3(c) shows interferograms at two different times for a jet set pressure of 320 Pa. As is evident from this interferogram, the surface shear stress field seems to have a local peak on the centerline due to the construction of the wall jet. Also evident is the decreased spacing of the fringes as distance from the jet exit increases indicating that the wall shear stress is dropping. By analyzing these data, surface shear stress across the image can be determined and averaged to determine an effective surface shear stress acting on the sensor.

Millimeter Scale Sensor

An important extension of the present invention is to take advantage of scale to make the dynamic-resonant sensor effective for measuring fluctuating surface shear stress. As the size of the sensor decreases, the frequencies at which it will resonate increase thereby increasing sensor bandwidth. Additionally, this smaller scale, higher frequency sensor will have a reduced sensitivity to lower frequency external noise and vibration. However, the effect of scale on the damping provided by the sensor is not known. The model of the sensor described above should assist in investigating the effects of scale, but verifying the model at these scales and gaining experience with small-scale sensors require that sensors of small scale be built and tested.

To investigate the effects of scale, sensors with dimensions on the order of 10 mm will be fabricated out of silicon. Fabricating sensors of this scale will be a challenge, and the expertise of NASA-Langley will be key to the success of developing these sensors. UW ActiveAero Center has signed a memorandum of agreement with NASA-Langley that will allow NASA personnel to assist in the adaptation of the current design and packaging (i.e. integration of electronics and connection to the macroscopic world) of these sensors. In addition, NASA has access to state-of-the-art micromachining and MEMS fabrication facilities that can manufacture the types of sensors discussed here at the millimeter scale. Materials personnel at NASA can also aid in the selection of actuation and

sensing components for the sensor. Evidence of NASA's willingness to participate in this activity and their manufacturing capabilities is provided in the Supplementary Documents section.

Once these sensors have been built, a characterization and calibration process similar to that described for the large-scale sensor will be carried out. The approaches for determining the static calibration and the effect of sensor on the flow is the same as discussed for the large-scale sensor. However, the dynamic calibration will be more complicated due to the higher bandwidth of these smaller scale sensors. As a result, new calibration methods, such as the Stokes layer excitation method described by Sheplak et al. (2002), and new calibration facilities will be required. Although the exact nature of these facilities will be part of the research conducted here, it is expected that a combination of facilities to be developed at UW and NASA-Langley will be used for in situ dynamic calibration.

The data collected while characterizing and calibrating this small-scale sensor will be used to verify the sensor model and to investigate scaling effects. In actual use, the sensor may be smaller than the scale tested here by an order of magnitude or more. In other applications, such as surface shear stress measurements on rough surfaces, larger scale sensors may be optimum. The testing at 100 mm and 10 mm scale will provide an initial set of data for developing scaling laws.

Open Loop Differential Sensing

Two individual dynamic resonant shear stress sensors may be used to create a differential shear stress signal. This would be done by having the motion of the two individual shear stress sensors 180 degrees out of phase. The forward moving platform would be retarded in its motion by the shear stress from the moving fluid significantly more than that of the backward moving platform. By appropriate phase inversion and signal subtraction a very fast response differential shear stress measurement can be obtained.

Closed Loop Feedback Differential Sensing

Two individual dynamic resonant shear stress sensors under closed loop control may be used to create a shear stress signal. This would be done by using analog or digital closed loop feedback control to force the motion of the two individual shear stress sensors to be precisely in-phase and/or equal amplitude. Only one of the moving platforms would be exposed to the fluid flow. The resonant motion of the platform exposed to the flow would be reduced by the damping effects of the surface shear stress. Additional forcing power would therefore be applied to the moving platform exposed to the fluid flow in order to keep the motion of the two moving platforms identical. The additional power would then be a signal which would be calibrated to the surface shear flow.

Sensor Array

To demonstrate one of the potential capabilities of these sensors, an array of sensors will be fabricated after the design and operation of the small-scale sensors has been verified. The size of the array and the number of sensors will depend on the experience gained while working with single sensors. Multiple sensor arrays would be valuable for many applications including dynamic transition detection and evaluating the effectiveness of a skin-friction drag reduction system. The array would take advantage of silicon fabrication techniques that are capable of fabricating many sensors on a single wafer. Before using these sensors for measurements, the array would be characterized and calibrated using the methods discussed above. One area that needs to be evaluated is the sensor-sensor interaction experienced by these dynamic sensors. This interaction will be evaluated by starting and stopping actuators and assessing their effect on the surface shear stress indicated by other sensors. This information will provide guidance for the spacing of future sensor arrays.

Once characterized, the array would be demonstrated in flows where fluctuating surface shear stresses are important. The first measurements would take place in a turbulent boundary layer where fluctuations in the fully turbulent region could be measured as well as fluctuations in the transition region. Another possible application of the array would be to characterize dynamic stall. Since surface shear stress is very sensitive to the onset of stall, the array could detect stall well before it actually occurs and capture the entire process at it occurs.